Six Sigma Based Approach to Optimize Radial Forging Operation Variables

A. K. Sahoo[†], M. K. Tiwari[&*] and A. R. Mileham[†]

Abstract

The present competitive market is focusing industrial efforts on producing high quality products with the lowest possible cost. To help accomplish this objective, various quality improvement philosophies have been put forward in recent years and of these Six Sigma has emerged as perhaps the most viable and efficient technique for process quality improvement. The work in this paper focuses on implementing the DMAIC (Define, Measurement, Analyze, Improve, and Control) based Six Sigma approach in order to optimize the radial forging operation variables. In this research, the authors have kept their prime focus on minimizing the residual stress developed in components manufactured by the radial forging process. Analysis of various critical process parameters and the interaction among them was carried out with the help of Taguchi's method of experimental design. To optimize the results obtained and to make the analysis more precise and cost effective, response surface methodology (RSM) was also incorporated. The optimized parameters obtained using Taguchi method and RSM were then tested in an industrial case study and a trade-off made to finalize the recommended process parameters used in manufacture.

Key Words: Six Sigma; Orthogonal array; Response surface methodology; Radial forging; Design of Experiment (DOE); S/N ratio; Analysis of variance (ANOVA)

[†] Department of Mechanical Engineering, University of Alberta, Edmonton, Canada

[&] Department of Forge Technology, National Institute of Foundry and Forge Technology, Ranchi, India.

[†]Department of Mechnical Engineering, University of Bath, Bath, UK

[*] Communicating author: mkt09@hotmail.com

1. Introduction

Radial forging is a unique process used for the precision forging of round and tubular components, with or without an internal profile. Since its development, this operation has found extensive use in both hot and cold forging operations. However it is sometimes confused in the literature with rotary forging [1]. Over the years, it has been continually improved and aimed towards automation, and the latest trend is the CNC integrated radial forging machine [2]. In addition, this process possesses the capability for the virtually chip less manufacture of rods and tubes to provide a precision-finished product with an excess of 95% material utilization [3]. Other common applications include the manufacturing of stepped, solid and hollow shafts; including axles for locomotives; preforms for turbine shafts, necks and bottoms of steel bottles, forged tubes for underwater drilling equipment; bars with round, square or rectangular cross section and forged tubes from 15 mm-1200mm in diameter and 25 to 100 mm in wall thickness, etc. Figure 1 illustrates some of the components manufactured by the radial forging process.

(Include Figure 1)

Components produced by radial forging typically have good mechanical and metallurgical properties and the process is generally preferred for the manufacture of high value added products. This process facilitates the manufacture of hollow products from solid blanks without piercing [1]. The foremost application of this process is the manufacturing of high pressure tubes for deep sea oil and gas pipe lines. Some of the economical benefits are:

- Material savings of up to 30 to 50 % are made possible in the manufacture of hollow products in comparison to products using technology involving drilling;
- Lower effort is needed in the manufacturing of hollow products;
- Reduction in load required by 2- 4 times;
- Forgings irrespective of length, size and material are easily manufactured.

Since radial forging operations have certain specific advantages as compared to other alternatives, there is a need for process improvement. The design of the process is still typically based on the trial and error method, which is very expensive and time consuming. In today's competitive environment, this is extremely undesirable due to the requirement of shorter production runs and lead times. Therefore, it is important in practice to identify the process parameters present in a radial forging operation and to optimize them. Lahoti *et.al.*(1976) [4] have contributed significantly by mathematically modelling the radial forging process. They implemented a slab method of analysis to develop a general model of the hot and cold radial forging of rods and tubes. Domblesky *et.al.* (1995) [5] used finite element based analysis to optimize the radial forging operation. Liou and Jang, (1997) [6] advocate a robust design methodology to optimize forging process parameters to give optimum stress distributions in products through FEM analysis. The above researchers have contributed significantly but in general they have not validated their work on the shop floor. In this research, we have addressed the problem from the implementation point of view. In recent years the Six Sigma philosophy has become a management philosophy and has helped in saving billions of dollars while improving customer satisfaction ratings and stock prices [7]. This paper focuses on the implementation of the Six Sigma philosophy in order to optimize the variables of the radial forging process.

As a systematic framework for quality improvement and gaining business excellence, the Six Sigma philosophy has become the paradigm of the industrial world in recent years. Some of the proven benefits of the Six Sigma system are productivity improvement, customer satisfaction, defect reduction, cycle time reduction, and culture change, etc [8]. From the view of statistics, this concept can be defined as a goal set for limiting the process variability within $\pm 6\sigma$ (i.e. total spread of 12σ) which leads to 3.4 defects per million opportunities (DPMO) for any process (Sigma or σ = standard deviation on the normal distribution). In order to meet with the lowest possible number of defects, the traditional three sigma limits are completely inadequate [9]. Six Sigma is a proven tool set for driving and achieving changes within a company. Moreover, it is a continuous improvement process, focusing on the customer requirements, process alignment, and analytical rigor. In order to accomplish the Six Sigma objectives, one of the most practiced methodologies is the DMAIC (Define, Measure Analyze, Improve and Control) approach [10]. Systematic and disciplined implementation of DMAIC ensures that the causes of defects are found and eliminated by focusing on process outcomes that are of critical importance to customers. Table 1 delineates the generic flow of the DMAIC approach.

(Include Table 1)

In this work, the prime focus is on minimizing the residual stress developed in components manufactured by the radial forging process. Thus, we have implemented DMAIC (Define, Measurement, Analyze, Improve, and Control) based Six Sigma approach to optimize the radial forging process variables and have made the process more robust to quality variations. Analysis of various critical process parameters and the interactions among them is carried out with the help of Taguchi's method of experimental design. Further, to improve the results obtained and make the analysis more precise and cost effective, response surface methodology (RSM) is also incorporated. Eventually, the optimized parameters obtained using Taguchi method and RSM are tested in a shop floor case study and a trade-off is made to finalize the recommended process parameters.

The remainder of the paper is organized in the following manner: In Section 2, we identify the problem environment. Section 3 describes the critical process measures that we have taken into consideration. Section 4 is devoted to the analysis stage of the DMAIC based Six Sigma approach. Further process improvement is made in Section 5. In Section 6 we conclude the DMAIC approach with the control phase. Results and discussion are provided in Section 7 and Section 8 concludes the research.

2. Define (Radial Forging)

Radial forging is a unique process for the precision forging of round and tubular components, with or without internal profiles, and for reducing the diameter of ingots and bars. Deformation in radial forging results from a large number of short stroke and high-speed pressing operations by two, three, or four hammer dies, arranged radially around the workpiece. A four hammer radial forging machine is shown in Figure 2(a) & 2(b). It is basically a short stroke mechanical press in which the stroke is initiated by means of eccentric shafts and these shafts are supported in housings that facilitate adjustment of the stroke. The part handling system can be equipped with either one or two workpiece manipulators, which differ considerably from others. In the radial forging operation, the axis of the workpiece is always maintained on the forging machine center line, irrespective of its diameter.

(Include Figure 2(a))

(Include Figure 2(b))

Correspondingly, the workpiece is gripped by a manipulator, which rotates it slowly and feeds it in the axial direction. A heated blank of round or polyhedral cross-section is pushed slowly into the forming unit where the blank is reduced in perimeter by radial positioned dies. During the forging of round cross sections, the chuck head rotates the workpiece in cycle with the forging hammers. The rotary movement of the chuck head spindle is synchronized with the hammer blows; therefore twisting of the workpiece is eliminated. Indexing positions can be set automatically for forgings of different cross sections. Table 2 depicts standard specifications of radial forging machines commercially available [1].

(Include Table 2)

The striking positions of connecting rods or dies are adjusted by rotating each of the adjustment housings through a link, adjustment nut and gear drive powered by a hydraulic motor while the stroke of the connecting rods is kept constant and short. This design permits high stroking rates of up to 220 strokes per minute in a large machine having a 100 T load capacity per forging tool. For example, a conventional radial forging machine of 1000 T is capable of forging blanks with a maximum diameter of 550 mm. The technology considered makes it possible to forge solid blanks of 1000-1200 mm into tubes of 900-1200 mm. There are more powerful radial forging machines (1600, 2500, 4000 tons, etc.) capable of manufacturing hollow forged products with diameters of 1500-3000 mm [1].

In the present problem, it is observed that components produced by radial forging face serious quality problems pertaining to their dimensional stability. Residual stress developed in forged components plays a crucial role in maintaining the desired dimension and surface quality. If present above a certain critical level, residual stress adversely affects the fatigue life and dimensional stability of components. Furthermore, it also causes stress corrosion in certain materials when used in a corrosive environment. Consequently, the product life cycle of components used in severe service conditions decreases. Also, the developed stress field may cause cracks to propagate rapidly [11]. Therefore, we have kept the focus of this research as investigating the influence of various process parameters on residual stress developed during the radial forging operation and consequently, optimizing the process parameters. In this context, we have considered the radial forging of gun tubes. Thus, the different process variables taken into account are defined in Table 3.

(Include Table 3)

3. Measure

After intense brain storming, several influencing and controllable process parameters were identified and measured. Out of which, the most significant contributors considered in the current research are the friction factor, length of die land, inlet angle, percentage reduction and corner fillet radius.

- Friction factor: Friction between the tool and the workpiece plays an important role in the radial forging process. The total radial load is very much influenced by the frictional force over the tool-workpiece interface. Moreover, the radial pressures in the forging and sizing zones increase substantially with increasing friction, while keeping the other variables constant.
- Length of die land: With increasing length of the die land, the total radial forging load increases and the metal flow toward the product is reduced because the neutral plane is shifted toward the die exit [3].
- Die inlet angle: With increasing inlet angle, the plastic deformation under the dies during radial forging is found to decrease because the load per tool decreases.

- Percentage reduction: As expected, the magnitude of the load increases with an increase in the percentage reduction in cross sectional area.
- Corner fillet: Prior experience reveals that the presence of a corner fillet plays a crucial role depending upon the characteristics of the job.

Figure 3 shows a schematic setup of a radial forging operation illustrating the die angle (θ) and die length (L).

(Include Figure 3)

During this stage, various process parameters were measured quantitatively and qualitatively. Performance measures of the existing process were determined by collecting data from the shop floor. Table 4 gives the experimental values of residual stress of 24 samples collected from the shop floor. The results were plotted on a control chart, as shown in Figure 4.

(Include Table 4)

(Include Figure 4)

Clearly, it is evident from the control chart that the process is not under control as the mean level of residual stress is very high. As the influencing parameters had been identified, their effect on the quality function could be tested. Figure 5 shows the cause and effect diagram drawn from the observed process conditions. From the given figure, it can be concluded that process effects such as cracks, notch-effect, dimensional instability and stress corrosion are some of the major consequences of too high a residual stress.

(Include Figure 5)

4. Analyze

In this stage of six sigma implementation, the goal is to substantiate a valid relationship between the process parameters and their corresponding response variables, and hence, to identify the critical parameters those have a significant contribution in influencing the response functions. In this context, Taguchi's method of experimental design is a viable methodology which not only provides the maximum amount of information with the minimum number of trials but also establishes functional relationships between the input and output variables [12]. The idea is to identify the critical parameters, increase system robustness, reduce experimental costs, and improve product quality. In this subsection, we explore Taguchi's experimental design principle to identify the optimal parameter settings.

Selection of Orthogonal Array

Nonlinear behaviour of the parameters of a process can be determined if more than two levels are used [13]. Therefore, parameters are analyzed at more than two levels. As mentioned earlier, five parameters or factors are considered important to this experiment viz. factor A: inlet angle, factor B: friction coefficient, factor C: percentage reduction, factor D: length of die land, and factor E: corner fillet. Table 5 depicts the various parameters with their corresponding levels. The levels of each of the parameters were decided from prior experience and the existing conditions. The response variable was as discussed, residual stress.

(Include Table 5)

Also, there was considered to be high probability of a strong interaction effect between the various process parameters. Hence, it was decided to study the interaction effects of these parameters on the level of residual stress. Thus the interaction between the inlet angle and friction coefficient (AxB), friction coefficient and % of reduction (BxC) and the inlet angle and % reduction (AxC) were tested. The total number of degrees of freedom (DOF) for four factors at three levels and one factor at two levels and three interactions are found to be ‘22’. Therefore, a three level orthogonal array with at least ‘22’ DOF was selected. From the Taguchi’s orthogonal inner arrays, the L_{27} (3^{13}) design for controllable factors as shown in Table 6 was selected.

(Include Table 6)

This array assigns 27 experimental runs and has 13 columns. The linear graph for the L_{27} (3^{13}) orthogonal array is shown in Figure 6. Each circle in the linear graph represents a column within the orthogonal array. The arc represents the interaction between the two factors displayed by circles at each end of the line segments. The number accompanying the line segment represents the column within the array to which the interaction should be assigned.

(Include Figure 6)

According to the linear graph, column 1, 2, 5 in L_{27} (3^{13}) are assigned to factors A, B, and C, and columns 3 and 4 are reserved for the interaction between A and B. Similarly, columns 6 and 7 are assigned to A and C and columns 8 and 11 are reserved for B and C. The remaining factors D and E are randomly assigned to columns 9 and 10 as illustrated in Table 6. Other columns are left unassigned. A similar design can be found in Syrcoss, 2003 [13]. Moreover, Factor E: corner fillet is at two levels, for this a dummy level technique is used to assign column 10 which is a 3-level column. Hence, level-3 of column 10 is assigned as level-1 of factor E as shown in Table 7. The resulting array after applying dummy level technique is still proportionally balanced and hence, maintains orthogonality [14].

Experimental Procedure

In order to pursue the experimental work, a high performance BNX 1400 (100mmx500cm) four-hammer radial forging machine was used to produce a test piece having dimensions of 30mmx500mm. Five repetitions are taken for the same experimental setting and the data obtained are documented in Table 7.

(Include Table 7)

As shown in Table 7, for each of the 27 trial conditions, response values were recorded. Subsequently, the data collected were used to analyze the mean response. Since the residual stress is a case of smaller the better, the objective function selected or the signal to noise ratio (S/N) to be maximized is taken as

$$\eta = -10\log_{10}\left(\frac{\sum y_i^2}{n}\right) \quad \text{..........................} \quad (1)$$

where y_i is residual stress and 'n' is number of experiments.

The S/N ratios are computed for each of the 27 trial conditions and tabulated as shown in Table 7. The average values of S/N ratios for each parameter at levels 1-3 are illustrated in Table 8 and the main effects of the various parameters when changed from the lower to higher level are plotted in Figure 7.

(Include Table 8)

(Include Figure 7)

From the response graph, the optimum levels of parameters were found as inlet angle (A_3), friction coefficient (B_1), percentage reduction (C_3), die land length (D_1) and corner fillet (E_2), respectively.

Analysis of Variance

An ANOVA analysis was performed to establish the relative significance of the individual factors. In Table 9, DOF is the degree of freedom, SS is the sum of squares, MS is the mean squares or estimated variance, F is the variance ratio. In ANOVA, the F ratio determines whether an effect is insignificant, so whether an effect is strong cannot be determined only by its SS. An effect's degrees of freedom should also be considered, i.e., an effect's mean square (MS) should determine whether an effect is weak-the smaller an MS, the weaker the effect. After comparing the results by using SS and MS to select the weak effects, Shiau (1989) [15] determined that MS was the better criterion to pool the weak effects. Table 9 shows that the inlet angle is the most critical parameter contributing up to 73.88%. Next is the friction coefficient contributing up to 9.28%. Also, Table 9 illustrates the percentage contributions of the various interaction effects. For example, it can be concluded that as compared to interaction effect AxB, AxC and BxC are more significant.

(Include Table 9)

The results obtained from the Taguchi experimental design can be fine-tuned by incorporating response surface methodology (RSM) [16]. Hence, it was decided to implement RSM methodology in this research to make the analysis more precise and accurate in the improve phase of the Six Sigma implementation.

5. Improve

In this stage of the Six Sigma implementation, the results obtained from the DOE analysis were further considered for augmentation. The main objective was to optimize the settings of the critical parameters. Therefore, Response Surface Methodology (RSM) was employed to establish a robust regression model and find possible optimized results. In the next subsections, the response surface methodology implementation is discussed.

Response Surface Methodology

In recent years, a plethora of research papers have documented the implementation of response surface methodology addressing various problems. This has certainly substantiated the credibility of this optimal search technique. RSM is a viable technique for this problem. It is basically a sequential procedure for fitting a series of regression models to the output variables [17]. The basic objectives of this technique may be summarized as follows:

1. Estimating a functional relationship between one or more responses and a number of independent variables that influence the responses.
2. Searching and exploring the optimum operating conditions for the system.

Conventionally, implementing the RSM methodology starts with a linear regression model as follows:

$$E(y) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots\ldots\ldots + \beta_k x_k \quad \ldots\ldots\ldots (2)$$

A low order polynomial is generally selected to approximate the true function in some region of the independent variable [17]. Thereafter, a higher order polynomial is employed to search for the general vicinity of the optimum region. However, in this case the second order model was used to improve the optimization process, a concept which significantly saved analysis time. A typical fitted second order model is of the form:

$$\hat{y} = \hat{\beta}_0 + \sum_{i=1}^{k} \hat{\beta}_i x_i + \sum_{i=1}^{k} \hat{\beta}_{ii} x_i^2 + \sum_{i<j}\sum \beta_{ij} x_i x_j \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where ‘k’ is the number of factors, ‘x_i’ represents the process parameter and ‘ β_i’ is the regression coefficient .

In matrix format the second order model can be expressed as:

$$\hat{y} = \hat{\beta}_0 + x'b + x'Bx \text{ ....(4)}$$

where

$$b = \begin{pmatrix} \hat{\beta}_1 \\ \hat{\beta}_2 \\ \vdots \\ \vdots \\ \hat{\beta}_k \end{pmatrix} \qquad \text{and} \qquad x = \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ \vdots \\ x_k \end{pmatrix},$$

While ‘B’ can be expressed as

$$B = \begin{pmatrix} \hat{\beta}_{11} & \hat{\beta}_{12}/2 & .. & .. & \hat{\beta}_{1k}/2 \\ \hat{\beta}_{12}/2 & \hat{\beta}_{22} & .. & .. & \hat{\beta}_{2k}/2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \hat{\beta}_{ik}/2 & .. & .. & .. & \hat{\beta}_{kk}/2 \end{pmatrix} \text{ .... (5)}$$

Least square estimate method is used to construe estimated regression coefficients given as:

$$\hat{\beta} = \begin{pmatrix} \hat{\beta}_0 \\ \hat{\beta}_i \\ \vdots \\ \vdots \\ \hat{\beta}_k \\ \vdots \\ \vdots \\ \hat{\beta}_{kk} \end{pmatrix} = \left(X'X\right)^{-1} X'y \text{ .... (6)}$$

Where ‘ X ’ are process parameters and can be represented as:

$$X = \begin{pmatrix} 1 & x_{11} & x_{21} & .. & .. & x_{k1} \\ 1 & x_{12} & x_{22} & .. & .. & x_{k2} \\ \vdots & \vdots & \vdots & & & \vdots \\ \vdots & \vdots & \vdots & & & \vdots \\ \vdots & \vdots & \vdots & & & \vdots \\ 1 & x_{1n} & x_{2n} & .. & .. & x_{k3} \end{pmatrix} \text{ .... (7)}$$

And ‘y’ is response which is expressed as:

$$y = \begin{pmatrix} y_1 \\ y_2 \\ : \\ : \\ : \\ y_n \end{pmatrix} \quad \text{..} \ (8)$$

On comparing the partial derivatives of regression equation to zero, the optimum levels of process parameters can be found.

$$\frac{\partial \hat{y}}{\partial x_1} = \begin{pmatrix} \frac{\partial \hat{y}}{\partial x_1} \\ \frac{\partial \hat{y}}{\partial x_2} \\ : \\ : \\ \frac{\partial \hat{y}}{\partial x_k} \end{pmatrix} = \frac{\partial}{\partial x}\left(\hat{\beta}_0 + x'b + x'\mathrm{B}x\right)$$

$$= b + 2\mathrm{B}x$$
$$= 0$$

The point $x_0 = (x_{10} \quad x_{20} \quad .. \quad .. \quad x_{k0})$ is called the stationary point and is expressed as:

$$x_0 = -\frac{1}{2}\mathrm{B}^{-1}b \quad \text{...} \ (9)$$

In our case, 27 experimental trials are conducted as shown in the previous section. Based on these experiments, the significant contribution of the five process parameters were evaluated using the F-ratio as shown in Table 9. ANOVA analysis also illustrates that the linear effect and square effect of each parameter and two way interactions (among friction coefficient, inlet angle, percentage reduction) should be taken into account. Hence, the second order model is considered to develop the regression equation between the process variables and the response. As shown in Figure 7, the corner fillet contributes minimum the to the response function. Consequently, the authors have adopted the following coding pattern and developed the coded variables for inlet angle, friction coefficient, percentage reduction and die land length, respectively.

$$x_i = \frac{[(Real\,value\,of\,\xi) - \lambda]}{\varsigma}$$

Where 'ξ'is the natural factor with 'ξ_{max}'the maximum level of 'ξ'and 'ξ_{min}'the minimum level of 'ξ'and $\lambda = \frac{(\xi_{max} + \xi_{min})}{2}$ and $\varsigma = \frac{(\xi_{max} - \xi_{min})}{2}$.

For Inlet angle, $x_1 = \frac{(InletAngle - 17)}{5}$; for friction coefficient, $x_2 = \frac{(Friction\ Coefficient - 0.21)}{0.2}$;

For percentage reduction, $x_3 = \frac{(\% Reduction - 26)}{14}$; for die land length, $x_4 = \frac{(Die\ land - 6)}{2}$;

In order to simplify the analysis, the authors have not taken the corner fillet into consideration which was shown to have a very low percentage of contribution. Table 10 depicts the coded factors.

(Include Table 10)

By implementing the least square method, the regression coefficients can be found and the regression equation is built up as:

$$Z=209.9395 - 61.7593X_1 + 19.2189X_2 - 3.1808 X_3 + 6.3038 X_4 + 44.5602X_1^2 - 13.3668X_2^2 - 2.6736X_3^2 - 2.9380X_4^2 - 21.3888X_1X_3 + 16.4026X_2X_3 \quad \text{..............................} (10)$$

Since the interaction factor X_1 x X_2 or (A x B) is not significant as compared with X_1 x X_3 or (A x C) and X_2 x X_3 or (B x C), this interaction has not been included in the regression equation to simplify the analysis. In order to determine the optimal response point, the contour and mesh were developed using the MATLAB 6.1. Figure 8(a) & 8(b) shows the contour and the mesh surface for the regression coefficient.

(Include Figure 8(a))

(Include Figure 8(b))

6. Control

The Control stage is the last and final stage and its sole purpose is to update the preserve optimized response obtained from the experiments. For complete success of Six Sigma, proper documentation of the process is recommended. The critical process parameters are continuously monitored and the documentation maintained and updated with information like friction level between the die and workpiece interface, percentage reduction, length of die land, inlet angle and corner fillet, etc at regular intervals. Other process variables such as temperature of the workpiece, temperature of the die, machine stroke length, etc. are also noted down. Statistical quality control tools like control charts facilitate the monitoring of the process and will show if the process goes out of control at any point of time.

7. Results and Discussion

In this case study, we have implemented DMAIC based Six Sigma approach to optimize the operation variables of a radial forging operation. The Taguchi method of experimental design was applied to analyze the optimum levels of individual process parameters. Table 11 shows the results obtained from factorial design and provides an insight into the process parameters affecting the forging process. Thus, from the ANOVA analysis, it can be concluded that inlet angle has emerged as the most crucial and influential parameter; the friction coefficient is the second most significant parameter; the interaction effects between inlet angle, friction coefficient and percentage reduction are also quite significant and must be taken into account when designing further experiments.

(Include Table 11)

Furthermore, response surface methodology was employed to optimize the set of parameters to ensure a minimum residual stress. Table 12 gives the optimum conditions found by RSM for the radial forging operation.

(Include Table 12)

The optimum parameter values were then applied to the process and Table 13 shows the process sample data that was gathered from the shop floor over a period of time. A control chart drawn for the improved state illustrates that there is a considerable amount of reduction in residual stress as shown in Figure 9.

(Include Table 13)

(Include Figure 9)

8. Conclusions

The global market is becoming more and more quality conscious. To compete in such an environment, companies need to adopt an efficient technique that can assess and take a diagnostic approach to meet customer needs and expectations. Nowadays, the industrial world has realized that the Six Sigma philosophy is certainly a viable solution to their shop floor problems. This paper has substantiated the fact that the efficiency and performance level of the radial forging operation can be improved by adopting a Six Sigma approach. Using the response surface methodology to complement the results obtained by the Taguchi approach, a significant reduction in residual stress was obtained and hence the produce quality is improved. The procedure has been shown to be an efficient and effective procedure for achieving the optimum set of operating parameters for a particular product quality characteristic. A number of industrial experiments have been carried out to validate the results which indicate that the cost of the experimentation will be more than paid back by the increased efficiency and quality of the process.

References

[1] H. Hojas, G. f. Fertigungstechnik, M. mbH, Radial Forging, Metal Hand Book, ASME. Vol.14, 1988.

[2] E. Rauschnabel, V. Schmidt, Modern applications of radial forging and swaging in the automotive industry, Journal of Material Processing Technology, 35 (1992) 371-377.

[3] G.D. Lahoti, L. Liuzzi, T. Altan, Design of Dies for Radial Forging of Rods and Tubes, Journal of Mechanical Working Technology, 1(1) (1977) 99-109.

[4] G.D. Lahoti, T. Altan, Analysis of the Radial Forging Process for Manufacturing Rods and Tubes, ASME Transactions, Journal of Engineering for Industry, 98 (1) (1976) 265-271.

[5] J.P. Domblesky, R. Schivpuri, B. Painter, Application of the finite element method to the radial forging of large diameter tube, Journal of Material Processing Technology, 49, 57, (1995)

[6] J.H. Liou, D.Y. Jang, Forging parameter optimization considering stress distributions in products through FEM analysis and robust design methodology, International Journal of Mach. Tools Manufact. 37 (6) (1997) 775-782.

[7] P.S.Pande, R.P. Neuman, R.R. Cavanagh, The Six Sigma Way – How GE, Motorola, and Other Top Companies Are Honing Their Performance, McGraw-Hill, New York, 2000.

[8] J. Antony, M. Kumar, M.K. Tiwari, An application of Six Sigma methodology to reduce the engine-overheating problem in an automotive company, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 219 (8) (2005) 633–646.

[9] F.W. Breyfogle, J.M. Cupello, B. Meadows, Managing Six Sigma: A Practical Guide to Understanding, Assessing, and implementing the strategy that Yields Bottom-Line Success. Wiley, NY, 2001.

[10] H.D. Koning, J.Mast, A rational reconstruction of Six Sigma's breakthrough cookbook, optimizing six sigma strategies to improve your bottom line, First International Conference on Six Sigma, Glasgow, Scotland, 16-17th December, 2004.

[11] I.C. Noyan, and J.B. Cohen, Residual stresses in materials, Am. Science. 79 (1991) 142-147.

[12] J.A. Ghani, I.A. Choudhury, H.H. Hasan, Application of Taguchi method in the optimization of end milling parameters, Journal of Materials Processing Technology, 145 (2004) 84-92.

[13] G.P. Syrcos, Die casting optimization using Taguchi methods, Journal of Materials Processing Technology, 135 (2003) 68-74.

[14] S.H. Park, Robust design and analysis for quality engineering, 1st edition, Chapman and Hall 1996.

[15] Y.R. Shiau, Determining the capability of a machine vision system by using Taguchi methods. M.S Thesis, Auburn University, AL, USA 1989.

[16] G.E.P. Box, N.R. Draper, Empirical Model Building and Response Surfaces, Wiley, New York 1987.

[17] J.S. Shang, S Li, P. Tadikamalla, Operational design of a supply chain system using the Taguchi method, response surface methodology, simulation, and optimization, International Journal of Production Research, 42 (18) 2004 3823-3849.

Figures

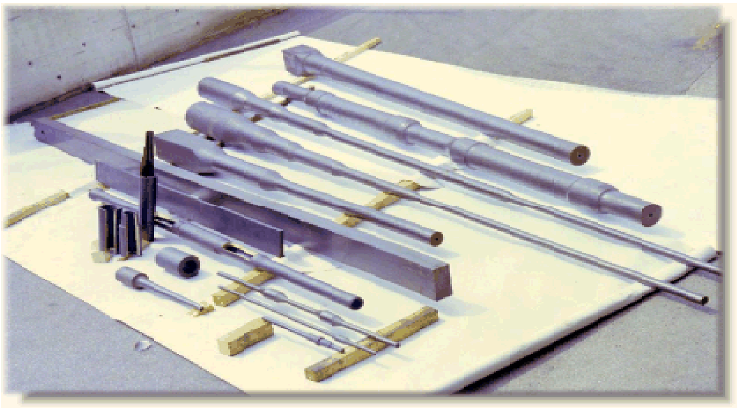

Figure 1: Forge components produced by Radial Forging

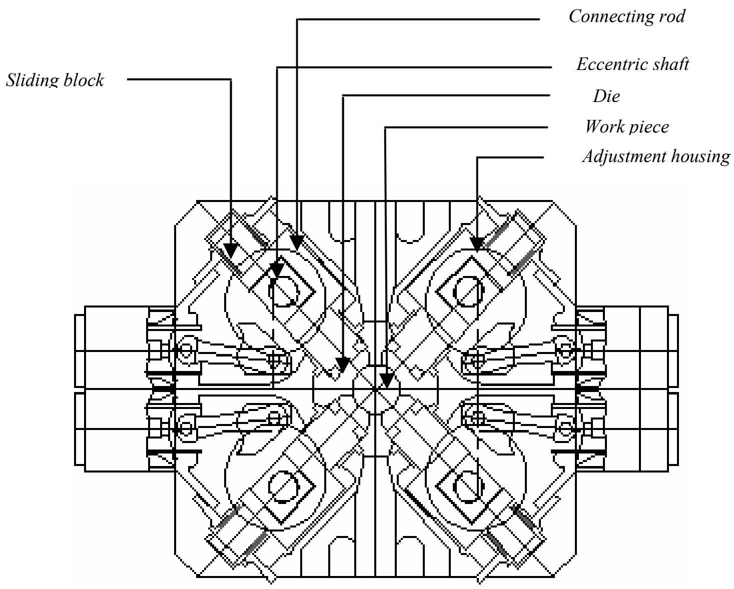

Figure 2(a): Cross sectional view of radial forging setup

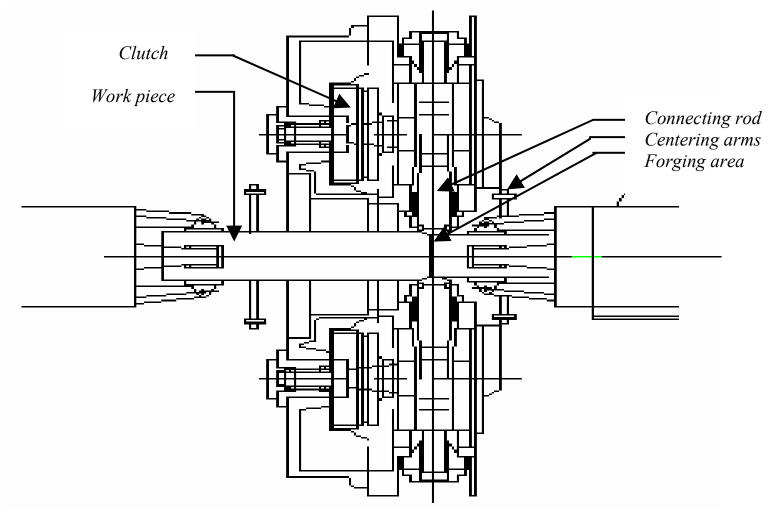

Figure 2(b): Longitudinal section view of radial forging setup

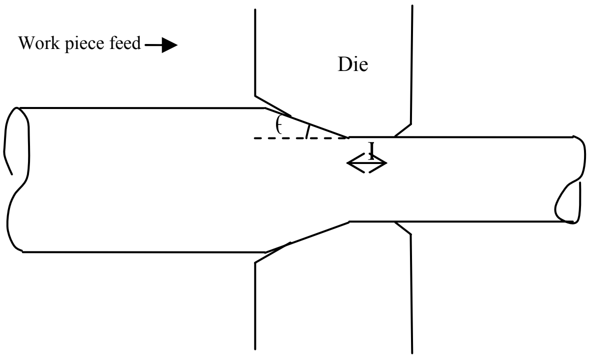

Figure 3: Radial forging operation

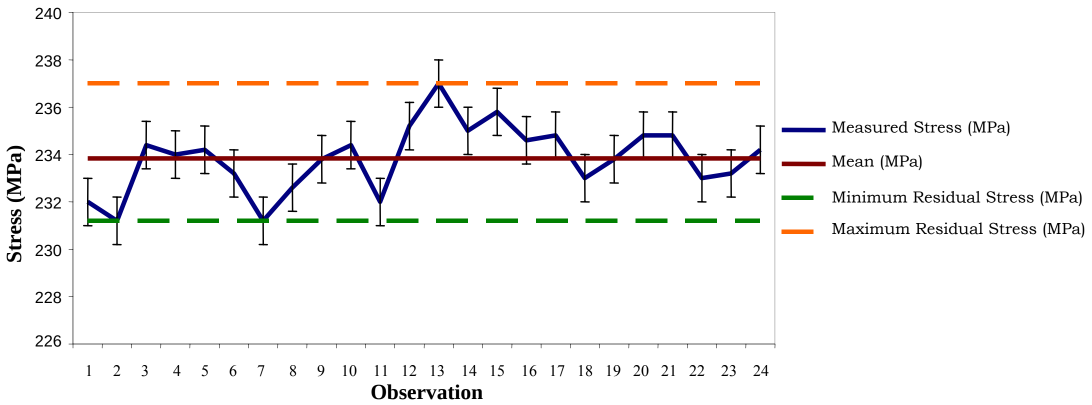

Figure 4: Control chart showing the existing process conditions

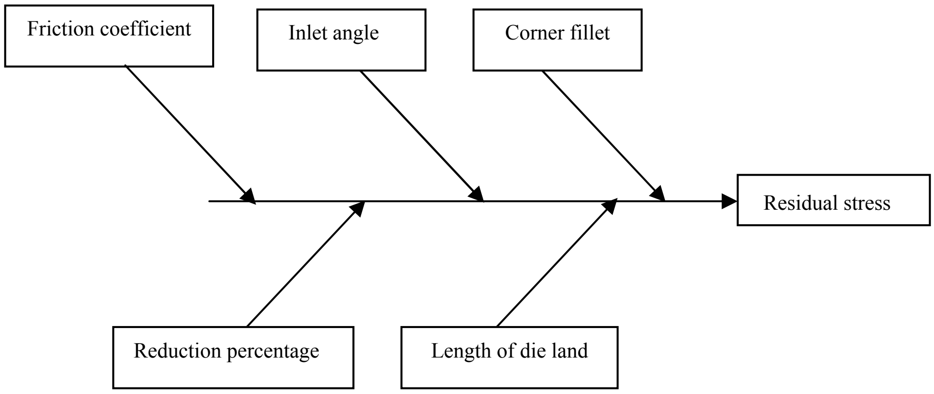

Figure 5: Cause and Effect diagram

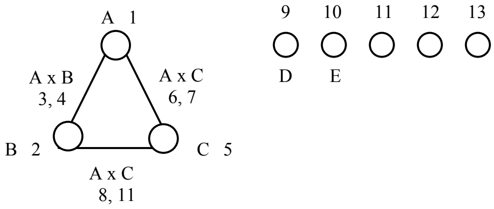

Figure 6: Linear graph for $L_{27}(3^{13})$ orthogonal array

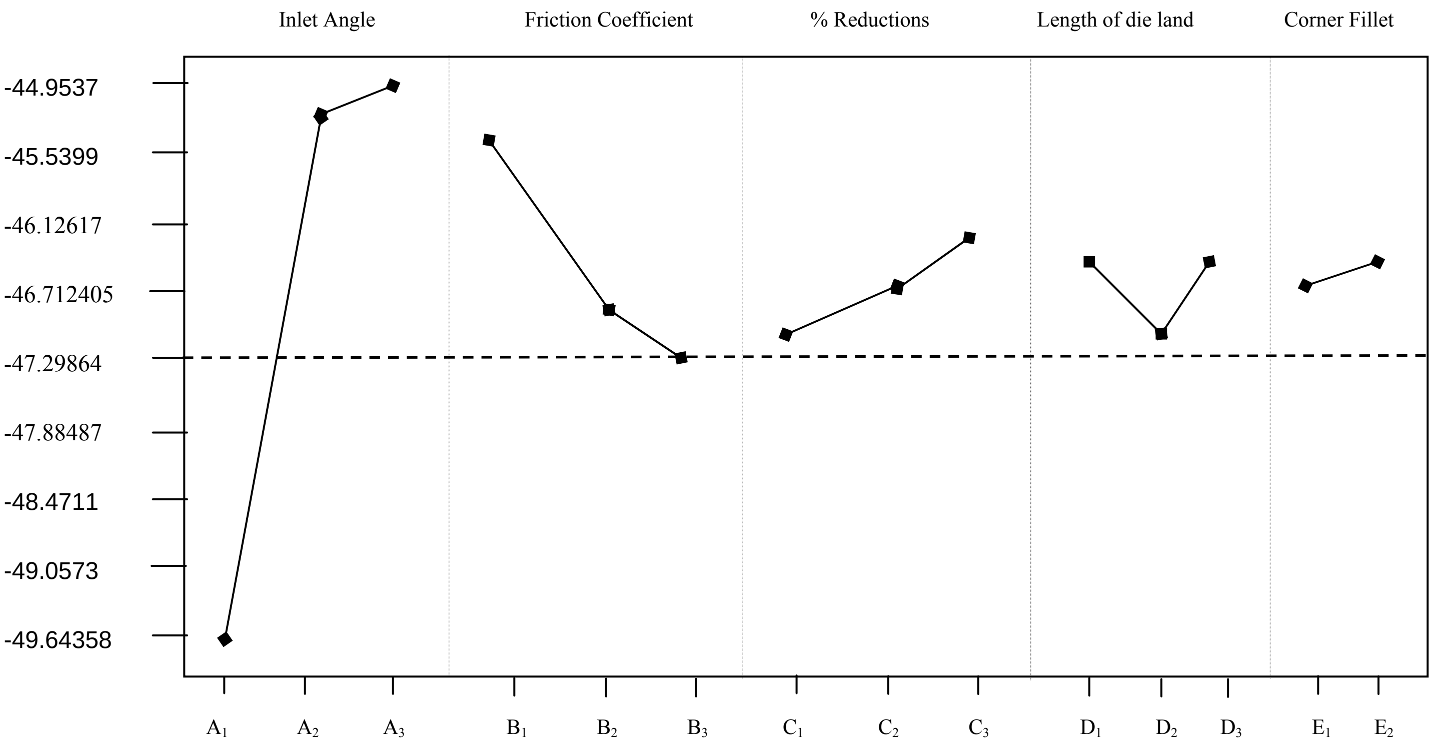

Figure 7: Main effects in terms of S/N ratio for residual stress

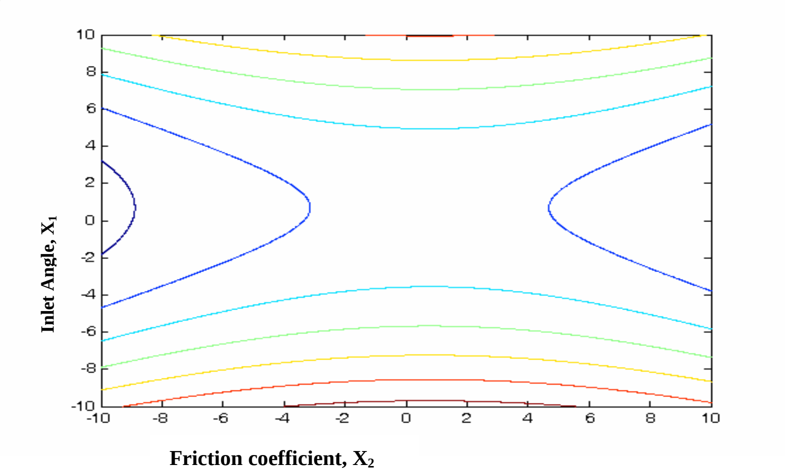

Figure 8(a): Contour plot illustrating the response surface for residual stress

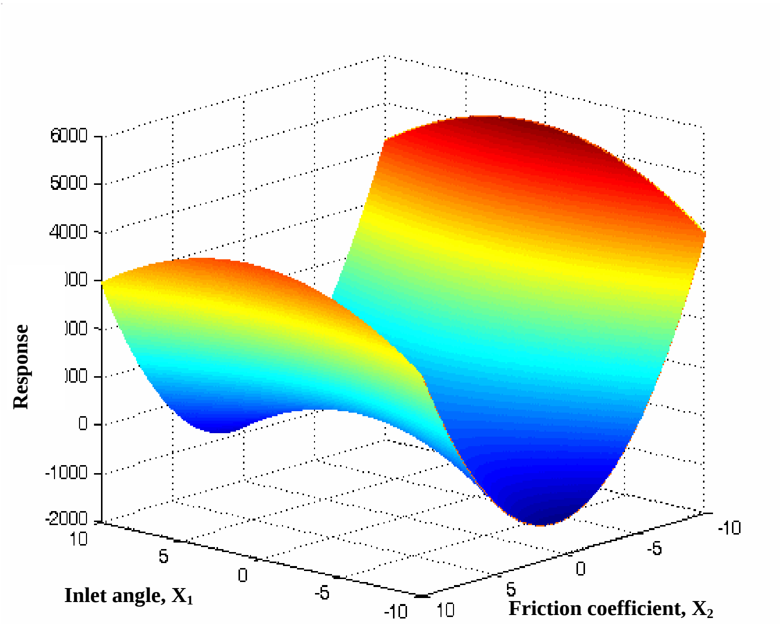

Figure 8(b): 3-D representation illustrating the response surface for residual stress

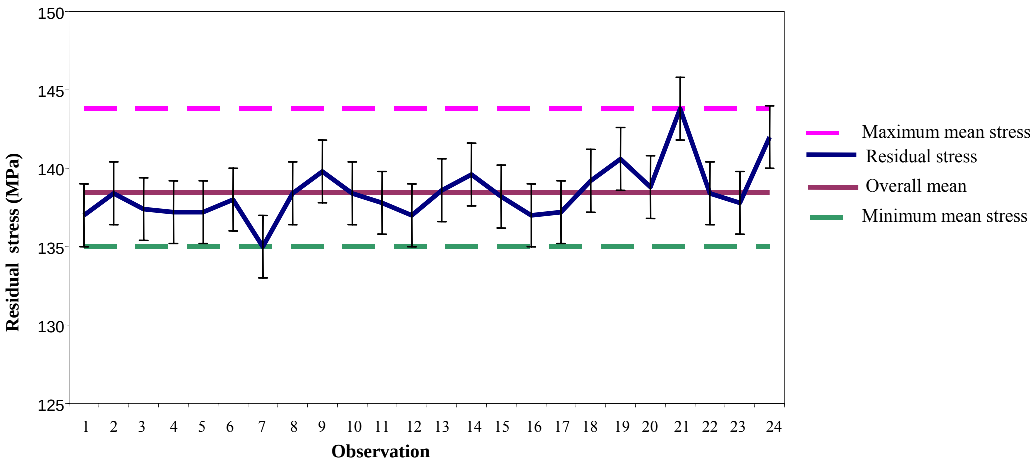

Figure 9: Control chart showing the improved process conditions

Tables

Table 1: Generic Flow of DMAIC approach in six sigma

Phase	Steps
Define	• Identify and map relevant processes. • Identify targeted stakeholder. • Determine and prioritize customer needs and requirements. • Make a business case for the project.
Measure	• Select one or more critical to quality (CTQ) functions. • Determine operational definitions. • Validate measurement system. • Assess the current process capability. • Define objectives.
Analyze	• Identify potential influence factors. • Select the vital few influence factors.
Improve	• Quantify relationship between control factors and CTQs. • Design actions to modify the process or settings of influence factors in such a way that the CTQs are optimized. • Conduct pilot test of improvement actions.
Control	• Determine the new process capability. • Implement control plans.

Table 2: Standard available sizes of radial forging machine

S/N	Proprietary Designation	Largest possible size for steel work		Smallest size forgeable for bar materials		Maximum length of finished work piece(m)	Maximum forging force per die(MN)	Number of blows per minute
		Round (mm)	Square (mm)	Round (mm)	Square (mm)			
1	SX-10	100	90	30	35	5	1.25	900
2	SX-13	130	115	35	40	6	1.6	620
3	SX-25	250	220	60	60	8	3.4	390
4	SX-40	400	360	80	80	10	8	270
5	SX-85	850	750	140	140	18	30	143

Table 3: Typical process variables in forging of gun tubes

Preform material:	AISI 1015 steel
Outside diameter of the preform:	290 mm
Inside diameter of the preform:	220 mm
Diameter of mandrel:	210 mm
Reduction in area (in percent):	10 – 40
Die inlet angle (degree):	3 – 20
Length of die land (mm):	15 – 45
Axial feed per stroke (mm):	5 - 30
Axial front pull force (kN):	0 – 1750
Axial back push force (kN):	0 – 2650
Average radial tool velocity (m/s):	0.1 – 1.5
Friction factor at tube- die and tube-mandrel interfaces:	0.15-1.0

Table 4: Process data collected for the existing process conditions

Sample No.	Residual Stress (MPa)					Mean(MPa)
	1	2	3	4	5	
1	240	140	205	275	300	232
2	243	135	210	265	303	231.2
3	242	136	210	277	307	234.4
4	240	137	207	276	310	234
5	241	138	205	274	313	234.2
6	241	139	204	270	312	233.2
7	239	137	204	271	305	231.2
8	242	138	205	269	309	232.6
9	243	139	207	270	310	233.8
10	242	140	206	272	312	234.4
11	241	141	204	273	301	232
12	240	145	210	271	310	235.2
13	245	144	209	276	311	237
14	244	143	205	275	308	235
15	244	142	210	274	309	235.8
16	241	142	206	277	307	234.6
17	242	142	209	276	305	234.8
18	243	139	205	274	304	233
19	241	139	207	273	309	233.8
20	243	140	209	274	308	234.8
21	244	140	208	273	309	234.8
22	241	142	205	271	306	233
23	241	138	203	277	307	233.2
24	243	139	206	274	309	234.2

Table 5: Control process parameters and their levels

Factor	Process parameters	Range	Level1	Level2	Level3	DOF
A	Inlet angle, θ (deg)	12-22	12	18	22	2
B	Friction coefficient	0.01-0.41	0.01	0.22	0.41	2
C	%reduction	12-40	12	28	40	2
D	die land , L (mm)	4-8	4	6	8	2
E	corner fillet		yes	no		1

Table 6: Orthogonal array $L_{27}(3^{13})$ taken into consideration

Trial	A 1	B 2	AXB 3	AXB^2 4	C 5	AXC 6	AXC^2 7	BXC 8	D 9	E 10	BXC^2 11	12	13
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	2	1	3	1	2
14	2	2	3	1	2	3	1	3	3	2	1	2	3
15	2	2	3	1	3	1	2	1	1	3	2	3	1
16	2	3	1	2	1	2	3	3	3	2	2	3	1
17	2	3	1	2	2	3	1	1	1	3	3	1	2
18	2	3	1	2	3	1	2	2	2	1	1	2	3
19	3	1	3	2	1	3	2	1	1	2	1	3	2
20	3	1	3	2	2	1	3	2	2	3	2	1	3
21	3	1	3	2	3	2	1	3	3	1	3	2	1
22	3	2	1	3	1	3	2	2	3	3	3	2	1
23	3	2	1	3	2	1	3	3	1	1	1	3	2
24	3	2	1	3	3	2	1	1	2	2	2	1	3
25	3	3	2	1	1	3	2	3	1	1	2	1	3
26	3	3	2	1	2	1	3	1	2	2	3	2	1
27	3	3	2	1	3	2	1	2	3	3	1	3	2

Table 7: Experimental results for residual stresses and their corresponding S/N ratios

Exp.No.	Inlet angle (degree)	Friction coefficient	% Reduction	Die land (mm)	Corner fillet	Residual Stress (MPa)					S/N Ratios
						1	2	3	4	5	
1	**1**	**2**	1	1	1	275	273	275	277	275	-48.78675
2	1	1	2	2	2	281	283	277	279	280	-48.94338
3	1	1	3	3	3 (1)	287	285	284	284	285	-49.09696
4	1	1	1	2	2	278	276	277	278	278	-48.86217
5	1	2	2	3	3 (1)	332	332	333	331	332	-50.42278
6	1	2	3	1	1	335	336	335	334	335	-50.50091
7	1	2	1	3	3 (1)	290	289	290	291	290	-49.24798
8	1	3	2	1	1	319	321	321	322	321	-50.12473
9	1	3	3	2	2	347	347	348	346	347	-50.8066
10	1	3	1	2	3 (1)	194	196	194	192	194	-45.75622
11	2	1	2	3	1	160	158	160	162	160	-44.08267
12	2	1	3	1	2	154	154	155	153	154	-43.75048
13	2	1	1	2	1	214	213	214	215	214	-46.60831
14	2	2	2	3	2	195	196	195	194	195	-45.80074
15	2	2	3	1	3 (1)	184	183	184	185	184	-45.29641
16	2	2	1	3	2	204	204	203	205	204	-46.19265
17	2	3	2	1	3 (1)	200	201	199	200	200	-46.02064
18	2	3	3	2	1	205	203	205	207	205	-46.23524
19	2	3	1	1	2	181	184	178	181	181	-45.15362
20	3	1	2	2	3 (1)	175	173	177	175	175	-44.82122
21	3	1	3	3	1	157	158	157	156	157	-43.9180
22	3	1	1	3	3 (1)	214	213	214	215	214	-46.60831
23	3	2	2	1	1	172	172	171	173	172	-44.71063
24	3	2	3	2	2	174	172	174	176	174	-44.81121
25	3	2	1	1	1	195	197	193	195	195	-45.80087
26	3	3	2	2	2	188	189	190	189	189	-45.52928
27	3	3	3	3	3 (1)	200	198	198	196	198	-45.93348

Table 8: Mean value of S/N ratios for each parameter level

factors	level1	level2	level3
inlet angle (degree)	-49.64358	-45.3179	-44.9537
friction coefficient	-45.52486	-47.0691	-47.3213
%reduction	-47.00188	-46.71734	-46.19597
die land (mm)	-46.4737	-46.9304	-46.5111
corner fillet	-46.7371	-46.4409	

Table9: ANOVA Analysis illustrating the significance level of various factors

Factor	DOF	SS	MS	F- ratio	% Contribution
A	2	119.4299971	59.715	3514.243	73.87726
B	2	15.00852	7.50426	441.6276	9.284002
C	2	3.51752	1.75876	103.5035	2.175875
D	2	1.36587	0.682935	40.1909	0.844903
E	1	1.19478	1.19478	70.31311	0.73907
A*B	4	0.059791111	0.014948	0.879681	0.036986
A*B*B	8	1.631624444	0.203953	12.00269	1.009294
A*C	4	4.286191111	1.071548	63.06086	2.651361
A*C*C	8	5.281268889	0.660159	38.8505	3.266898
B*C	4	3.993591111	0.998398	58.75597	2.470364
B*C*C	8	4.684424444	0.585553	34.45995	2.897701
Error	71	1.206451819	0.016992		0.746289
Total	80	161.66003	2.02075		100

Table 10: Coded values for the various factors

Inlet Angle (X_1)	Friction Coefficient (X_2)	% Reduction (X_3)	Length of Die Land (X_4)	X_1^2	X_2^2	X_3^2	X_4^2	$X_1 x X_3$	$X_2 x X_3$	Response Y (MPa)
-1	-1	-1	-1	1	1	1	1	1	1	275
-1	-1	0.142857	0	1	1	0.020408	0.020408	-0.14286	-0.14286	280
-1	-1	1	1	1	1	1	1	-1	-1	285
-1	0.05	-1	0	1	0.0025	1	1	1	-0.05	278
-1	0.05	0.142857	1	1	0.0025	0.020408	0.020408	-0.14286	0.007143	332
-1	0.05	1	-1	1	0.0025	1	1	-1	0.05	335
-1	1	-1	1	1	1	1	1	1	-1	290
-1	1	0.142857	-1	1	1	0.020408	0.020408	-0.14286	0.142857	321
-1	1	1	0	1	1	1	1	-1	1	347
0.2	-1	-1	0	0.04	1	1	1	-0.2	1	194
0.2	-1	0.142857	1	0.04	1	0.020408	0.020408	0.028571	-0.14286	160
0.2	-1	1	-1	0.04	1	1	1	0.2	-1	154
0.2	0.05	-1	0	0.04	0.0025	1	1	-0.2	-0.05	214
0.2	0.05	0.142857	1	0.04	0.0025	0.020408	0.020408	0.028571	0.007143	195
0.2	0.05	1	-1	0.04	0.0025	1	1	0.2	0.05	184
0.2	1	-1	1	0.04	1	1	1	-0.2	-1	204
0.2	1	0.142857	-1	0.04	1	0.020408	0.020408	0.028571	0.142857	200
0.2	1	1	0	0.04	1	1	1	0.2	1	205
1	-1	-1	-1	1	1	1	1	-1	1	181
1	-1	0.142857	0	1	1	0.020408	0.020408	0.142857	-0.14286	175
1	-1	1	1	1	1	1	1	1	-1	157
1	0.05	-1	1	1	0.0025	1	1	-1	-0.05	214
1	0.05	0.142857	-1	1	0.0025	0.020408	0.020408	0.142857	0.007143	172
1	0.05	1	0	1	0.0025	1	1	1	0.05	174
1	1	-1	-1	1	1	1	1	-1	-1	195
1	1	0.142857	0	1	1	0.020408	0.020408	0.142857	0.142857	189
1	1	1	1	1	1	1	1	1	1	198

Table 11: Improved operating parameters

Inlet Angle (degree)	Friction Coefficient	% Reduction	Length of Die Land (mm)	Corner Fillet
22	0.01	40	4	No

Table 12: Revised operating parameters

Inlet Angle (degree)	Friction Coefficient	% Reduction	Length of Die Land (mm)	Corner Fillet
19.751	0.0523	34.3286	8.1564	No

Table 13: Process data collected for the improved process conditions

Sample No.	Observation (MPa) 1	2	3	4	5	Mean
1	140	114	124	167	140	137
2	143	113	127	166	143	138.4
3	142	113	125	165	142	137.4
4	140	113	129	164	140	137.2
5	141	113	127	164	141	137.2
6	141	119	126	163	141	138
7	139	117	127	153	139	135
8	142	118	122	168	142	138.4
9	143	119	125	169	143	139.8
10	142	114	127	167	142	138.4
11	141	114	129	164	141	137.8
12	140	115	128	162	140	137
13	145	114	126	163	145	138.6
14	144	114	129	167	144	139.6
15	144	112	126	165	144	138.2
16	141	112	127	164	141	137
17	142	112	128	162	142	137.2
18	143	119	127	164	143	139.2
19	141	119	126	176	141	140.6
20	143	114	129	165	143	138.8
21	144	140	126	165	144	143.8
22	141	112	127	171	141	138.4
23	141	113	127	167	141	137.8
24	143	119	128	177	143	142